ERL Main Linac:
Overview, Parameters Cavity and HOM Damping

Matthias Liepe

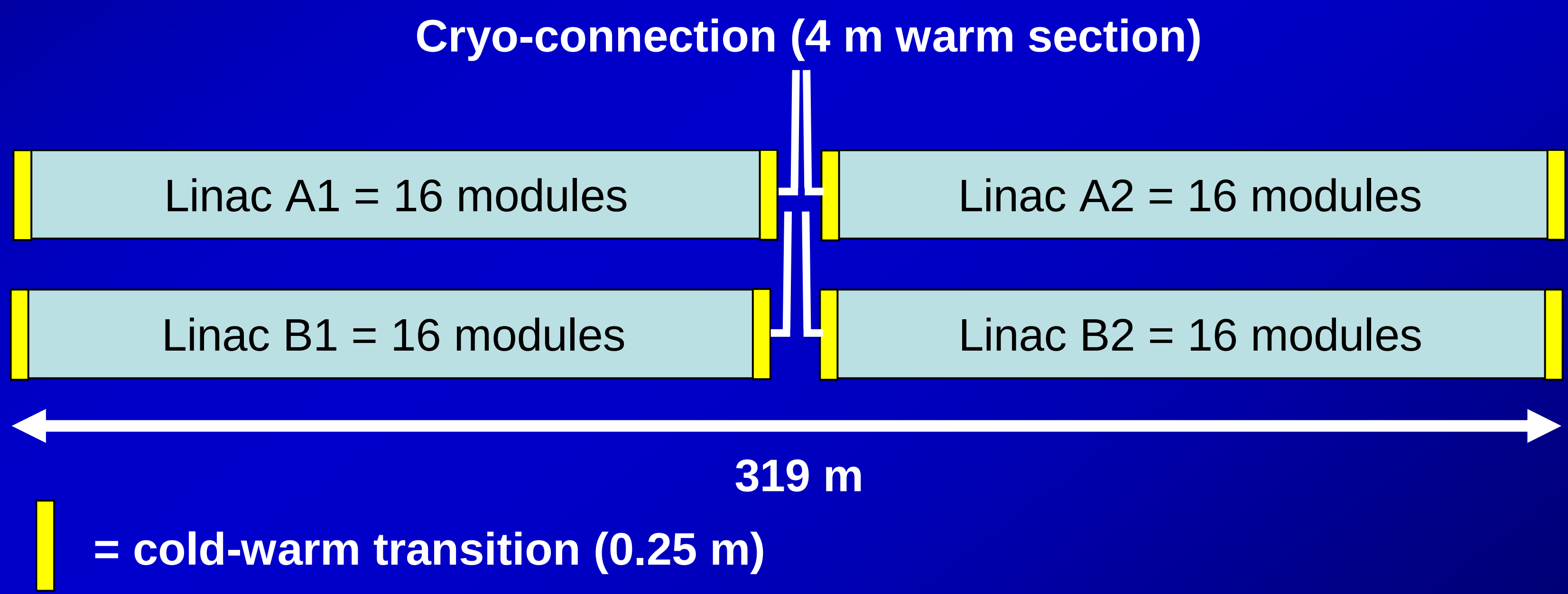
Outline

- **Overview**
  - Layout
  - Parameters and optimization
    - Gradient
    - Temperature
- **Cavity and HOM damping**
  - Overall concept
  - Cavity design
  - HOM beam line absorber
- **Test and R&D plans**

Layout
Parameters and Optimization

Linac Layout

- Main Linac Tunnel length: 319 m
- Cryo-module: 6 SRF cavities + 1 magnet package
- CW cavity operation!
- Linacs are in 2+2 sections to limit cryo-load per linac



Critical Parameters / Objectives

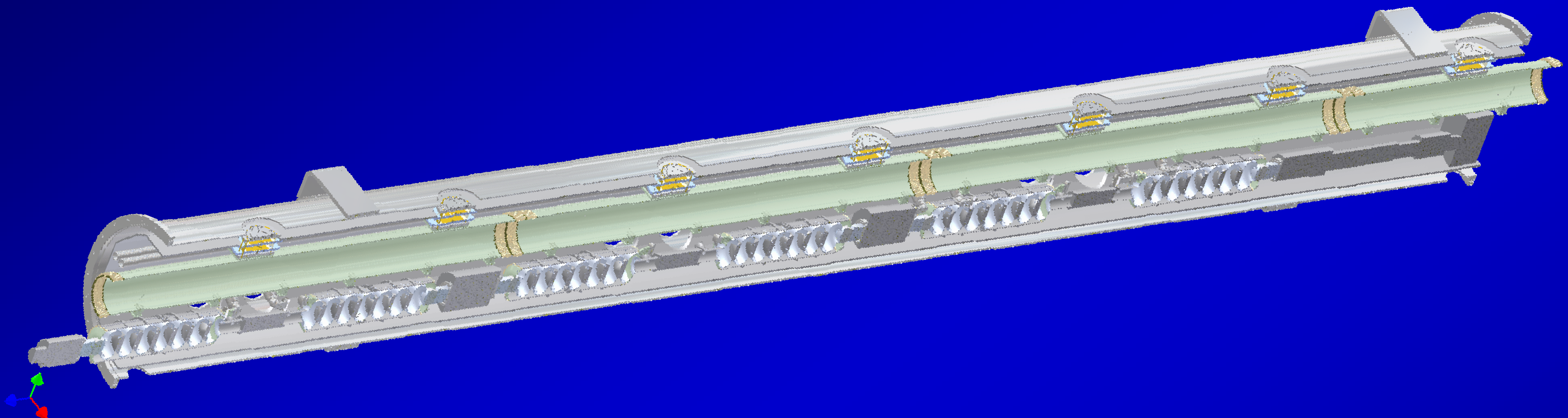
Parameter	Cornell ERL	XFEL	consequence
operation mode	CW	pulsed	250 * 2K load per cavity, factor ≈3 larger total 2K load
linac energy gain	5 GeV	20 GeV	
average current	0.1 A* 2	$3 \cdot 10^{-5}$ A	$(I_{ERL}/I_{XFEL})^2 = 4 \cdot 10^7$ $(P_{HOM,ERL}/P_{HOM,XFEL}) = 400$
bunch charge	77 pC	1 nC	
bunch length	2 ps	80 fs - 1 ps	f < 100 GHz for HOMs
emittance (norm.)	0.3 mrad · mm	1.4 mrad · mm	coupler ports
energy spread (rms)	2e-4	1.25e-4	Similar, but much higher beam current, Q_L!

- Accelerate / decelerate 100 mA beam to 5 GeV
- Minimize emittance growth
- Low trip rate
- Minimize cost (construction and operation)

Objectives and Challenges

- Operate SRF cavities <u>CW</u>
  - Very reliable operation essential
  - Avoiding excessive cryogenic loads
  - Minimize RF drive power
- Accelerate a <u>high beam current</u>
  - Avoiding beam instability and excessive HOM losses
  - Dispose high HOM power safely
- Preserve beam emittance
  - Small wake fields
  - Good cavity alignment
  - Small transverse kick fields from beam pipe asymmetries (input couplers, …)

Cryomodules



- 6 SRF cavities per module (tentative)
- Modules connect directly (no cold-warm transitions)
- All cryogenic piping is inside of the modules
- Details: Eric's talk…

ERL Main Linac: Technical Parameters I

Parameter	Cornell ERL	Comments / justification
Total linac length	629 m	for 5 GeV; fill factor lower due to larger number of magnets and longer, larger diameter beam tubes for HOM damping by beam pipe absorbers
Module length	9.8 m	
SRF cavities per module	6 (tentative)	
Total number of cavities	384	
Geometric fill factor	49 %	

- **Note: A very optimistic 65% fill factor (with XFEL type cavity beam tubes and a different HOM damping scheme) would reduce the total SRF linac cost (modules, RF, cryo, tunnel) by 2 % <u>(assuming same cost for HOM damping and same Q_0).</u>**

ERL Main Linac: Technical Parameters II

Parameter	Cornell ERL	Comments / justification
Cavity frequency	1.3 GHz	ILC technology available
Cells per cavity	7	Strong HOM damping; risk of trapped modes
Active cavity length	0.8 m	
Impedance per cavity (circuit definition)	400 Ohm	Iris radius optimized; trade-off between HOM losses and fundamental mode losses
Cavity Loss Factor	10 V/pC	
E_peak/E_acc	< 2.2	upper limit to reduce field emission
Average acc. gradient	16.2 MV/m	optimization (cost, field emission)
unloaded Q_0	$> 2 \cdot 10^{10}$	cost of cryogenic plant (largest contributor)
loaded Q	6.5e7 ($2 \cdot 10^{7}$ - $1 \cdot 10^{8}$)	optimized for 20 Hz peak detuning and 10 Hz typical detuning
Cavity full bandwidth	20 Hz	
Peak detuning	< 20 Hz	
Cavity offset tolerance	1 mm	Similar to ILC
Cavity angle tolerance	1 mrad	
Operating temp.	1.8 K	Optimization

ERL Main Linac: Technical Parameters III

Parameter	Cornell ERL	Comments / justification
Average HOM power per cavity	154 W	Overhead for resonance excitation of modes, dipole losses
Max. HOM power per cavity	300 W	
Average 1.8K Static load/Cavity	0.5 W	
Average 1.8K Dyn. load/Cavity	10.5 W	for $Q_0 = 2 \cdot 10^{10}$
Total 1.8 K static load	0.2 kW	
Total 1.8 K dynamic load	4 kW	for $Q_0 = 2 \cdot 10^{10}$
Total 5 K static load	2.3 kW	
Total 5 K dynamic load	3.1 kW	dominated by HOM losses; assumes that 5% of HOM power goes to 5K
Total 80 K static load	5 kW	
Total 80K dynamic load	60 kW	dominated by HOM losses

ERL Main Linac: Technical Parameters IV

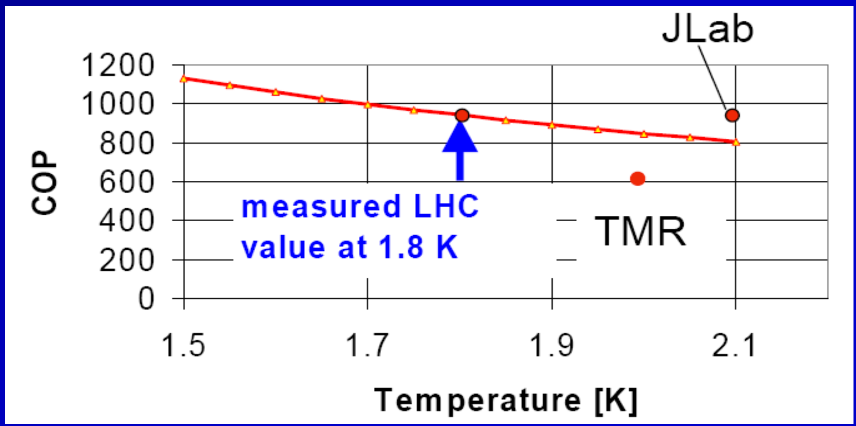
Parameter	Cornell ERL	Comments / justification
Ave RF Power/Cavity	2 kW	for 20 Hz peak detuning and 10 Hz typical detuning
Peak RF Power/Cavity	5 kW	
Number of Cavities/RF Unit	1	vector sum control difficult
Bunch to bunch energy fluctuation	$2 \cdot 10^{-4}$	Stability requirements similar to XFEL, but have to achieve this at much higher Q_L and with higher beam currents; see talk on LLRF
RMS field ampl. stab. uncorrelated	$5 \cdot 10^{-4}$	
RMS field ampl. stab. correlated	$1 \cdot 10^{-4}$	
RMS field phase stab. uncorrelated	0.15 deg	
RMS field phase stab. correlated	0.02 deg	

Optimal Operating Temperature

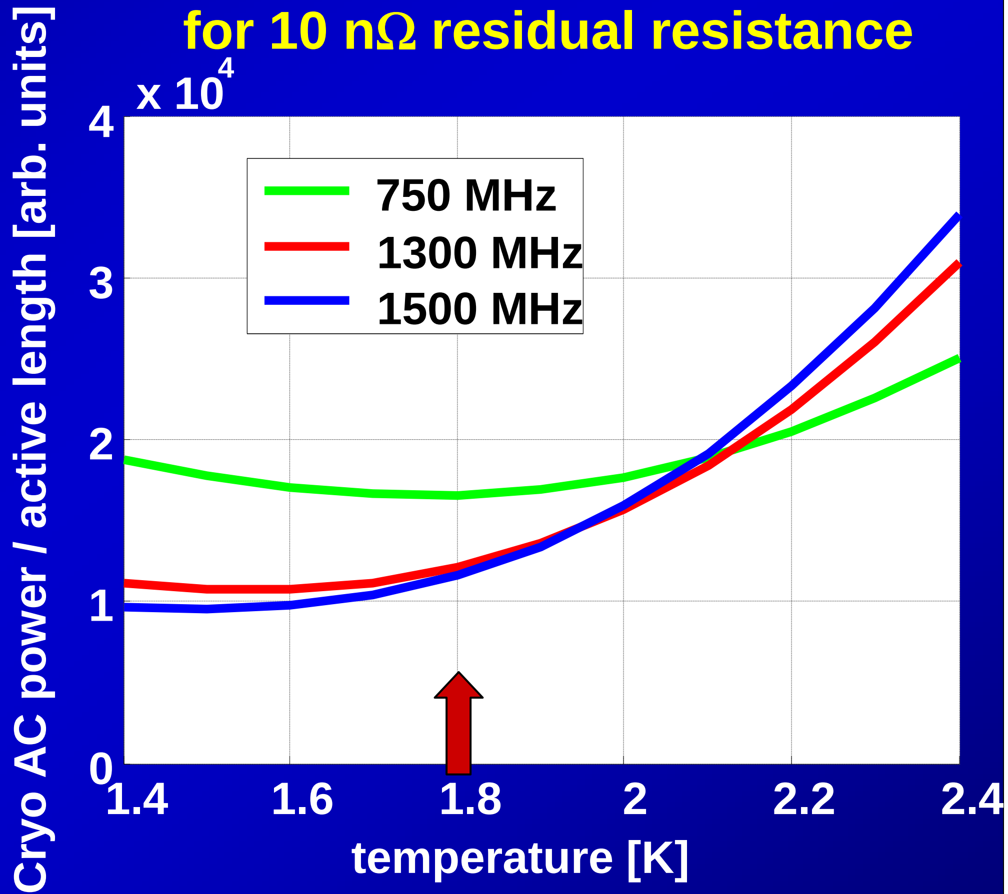
COP=1/(K * η CARNOT)

η CARNOT = T/(300 -T)

K= 0.176 (from latest LHC measurements at 1.8 K)



Bernd Petersen DESY



⇒1.8K (25% reduced AC power as compared to 2K)

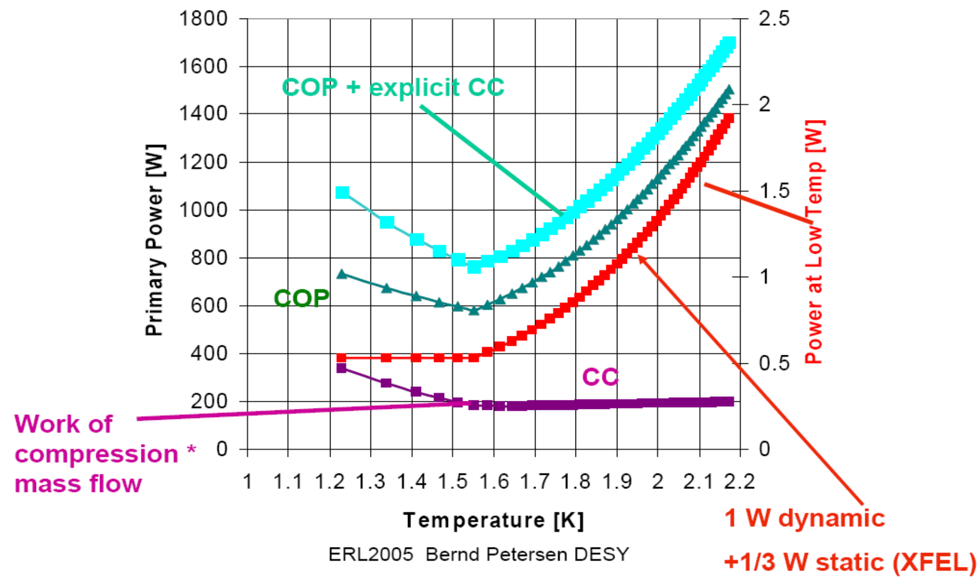
Note: T<1.8K is might cause instability in the cryo-system.

Cavity Operation at 1.8K

ERL2005: Bernd Petersen, DESY

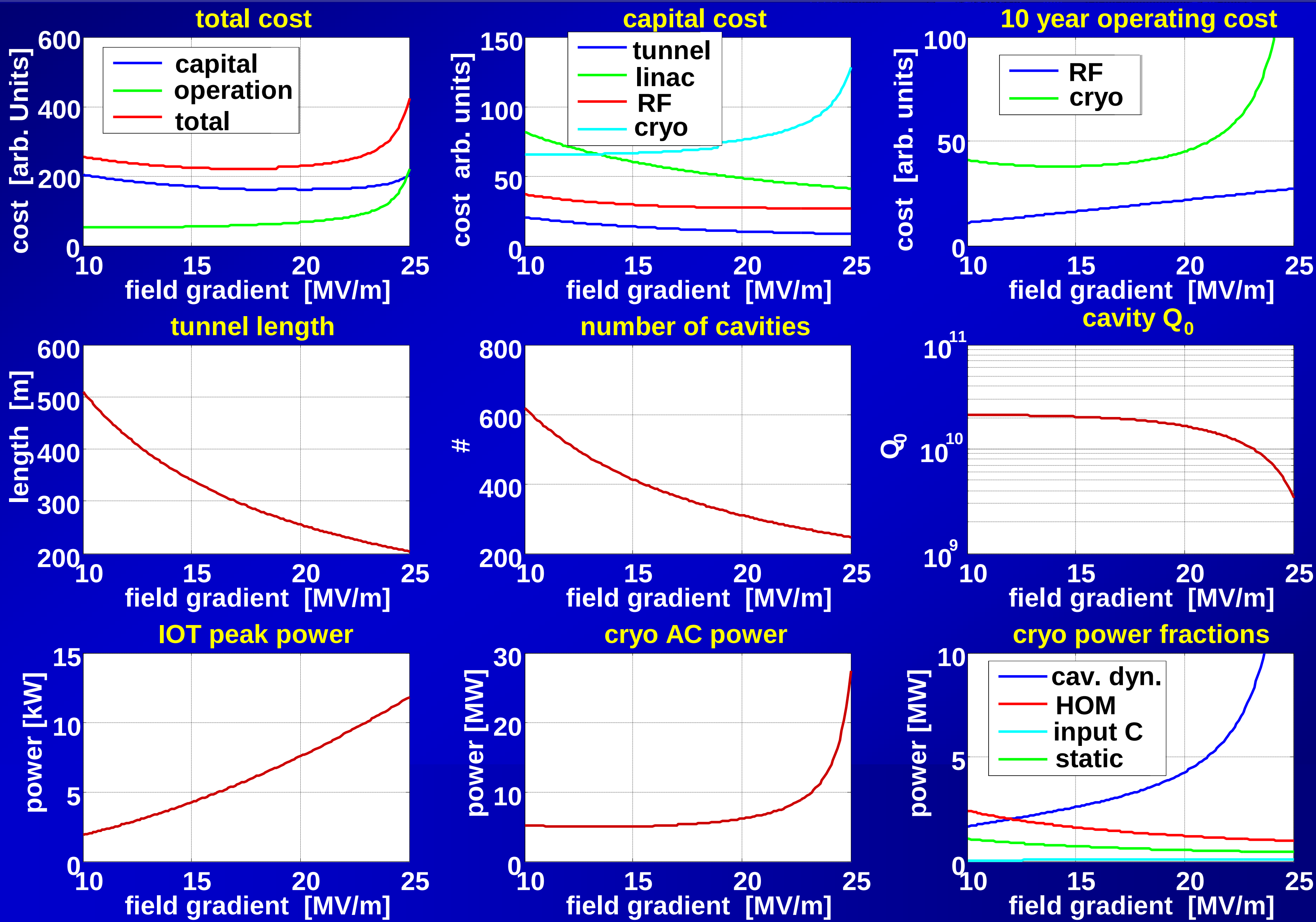
- **Lowering the temperature seems to be effective as long as Q = Q(T) follows BCS and the temperature dependent dynamic loads dominate (reasonable lower limit 1.5 K)**
- **HeII cooling might become unstable below 1.8 K – tests required**
- **Another cold compressor stage is required for each 0.2 K temperature step to lower temperatures – investment costs and system complexity increase**

All in one – the lower the better !?

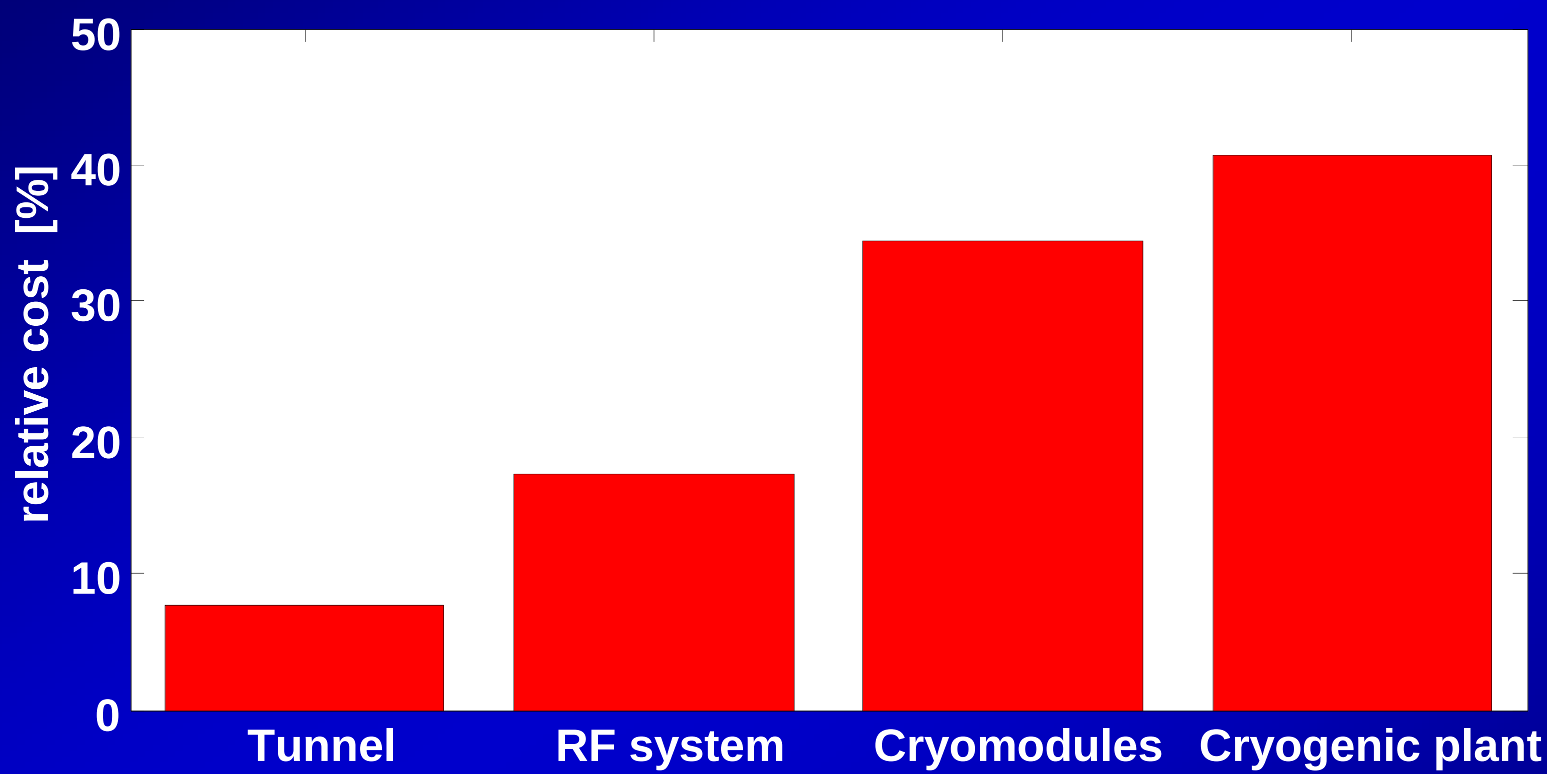


- **In view of pressure drops, critical gas velocities, work of compression and general sizing the lower gas densities at lower temperatures seem to be balanced by the lower cooling loads and the related lower mass flows**

Optimal Field Gradient I

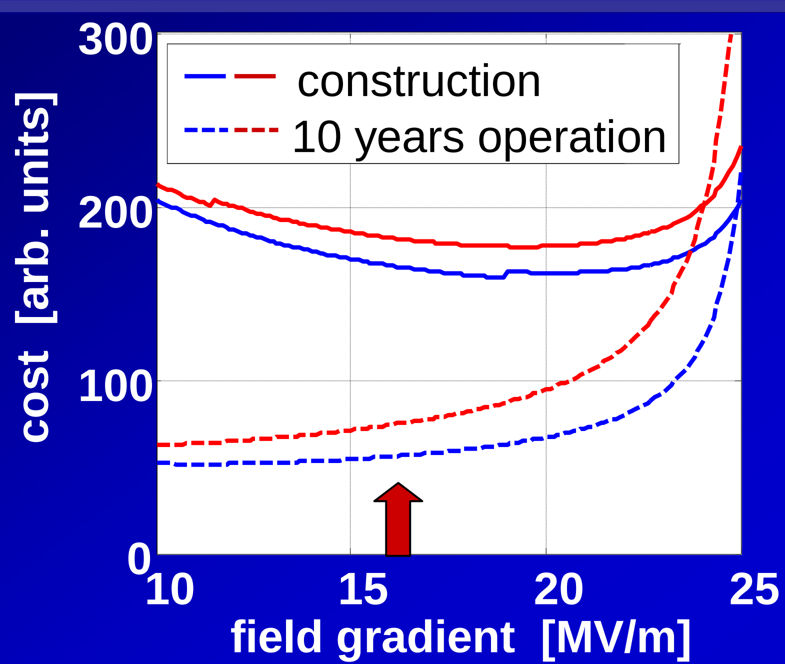


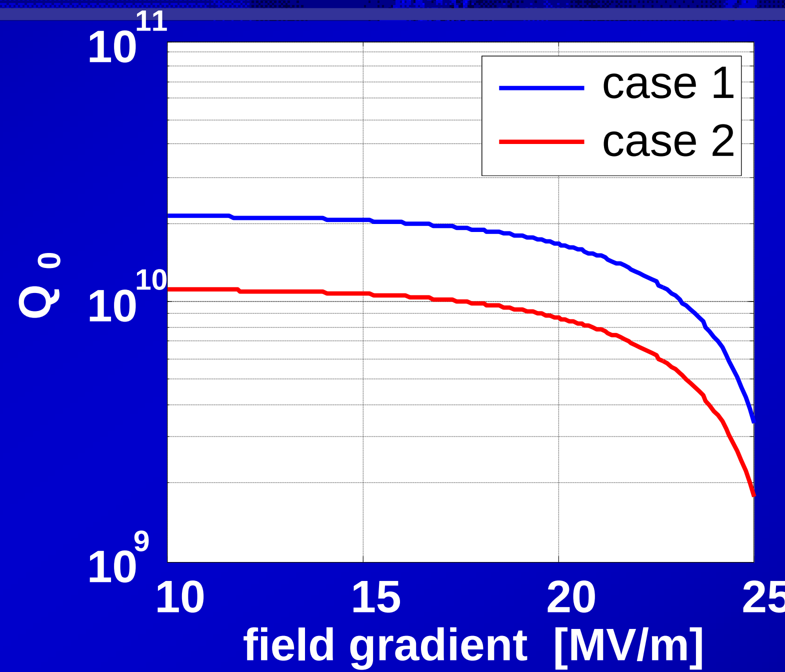
Main Linac Cost Distribution for E=16.2 MV/m



- Cryogenic plant and module costs dominate

Optimal Field Gradient II

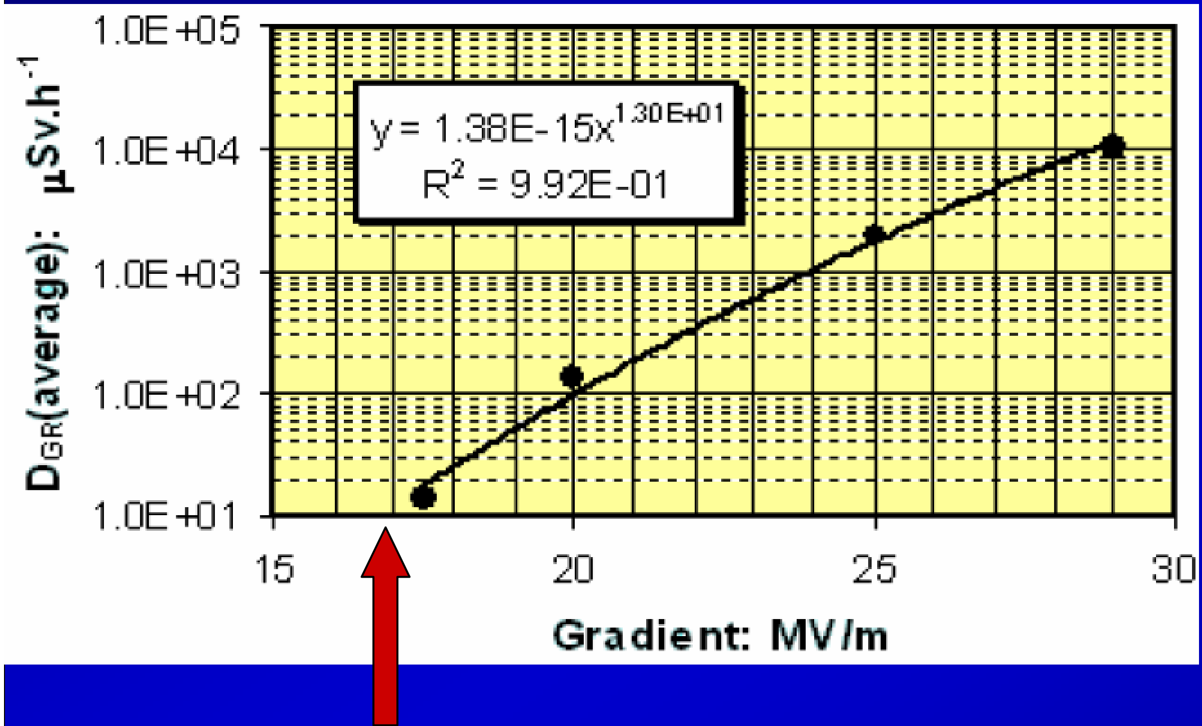




- Q_0-value has significant impact on cost (high impact parameter)
- Construction cost changes only moderately for gradients between 16 and 23 MV/m
- Operating cost / AC power increases with gradient
- Select gradient at lower end: ***16.2 MV/m*** ***⇒ Less risk for same cost!***

Field Emission

Gamma radiation measured at DESY/FLASH from cavity field emission:



For ERL : 10µGy/h * 200 (for cw)= <u>2 mGy/h = 0.2 rad/h</u>
10 years of operation: <u>100 Gy = 10,000 rad</u> (at 5000h/year)

- Exponential growth in FE with gradient
- Serious problem in <u>cw cavity operation</u>
- <u>Low trip rate essential for light source!</u>
- Favors lower gradients
- High reliability: don't push gradient and RF power to limit
- <u>*⇒ 16.2 MV/m*</u>

Cavity Performance Goals

– For gradient overhead: Require average cavity performance in linac: 18 MV/m at $Q = 2 \cdot 10^{10}$ with ±2 MV/m spread

⇒ Min. cavity performance in linac: 16 MV/m at $Q = 2 \cdot 10^{10}$

– Average operating gradient: 16.2 MV/m ⇒ 384 cavities!

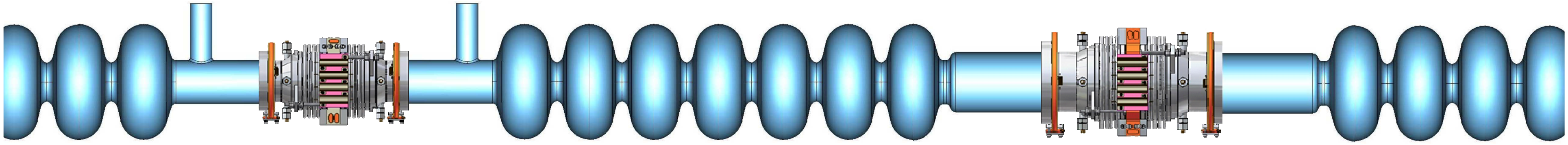
– This gives 12.5 % overhead for initial performance risks and failures (tuner, IOT, power supply…)

– Individual cavities can operate at gradients up to 20 MV/m

- Cryogenic system can support 20 MV/m at $Q = 1 \cdot 10^{10}$ for individual cavities
- RF power sufficient for 20 MV/m with <20 Hz peak detuning

Cavity and HOM damping

Overall Concept



1.8K 80K 1.8K 80K 1.8K

- 7-cell, 1.3 GHz SRF cavity
- HOM damping via beam line absorbers
  - Relative simple and quite effective concept
  - Avoids kicks from beam line asymmetries
  - Deals with high HOM power
  - Works well at high frequencies
  - Supports high Q_0 operation
- Fill factor is <u>not</u> a strong cost driver

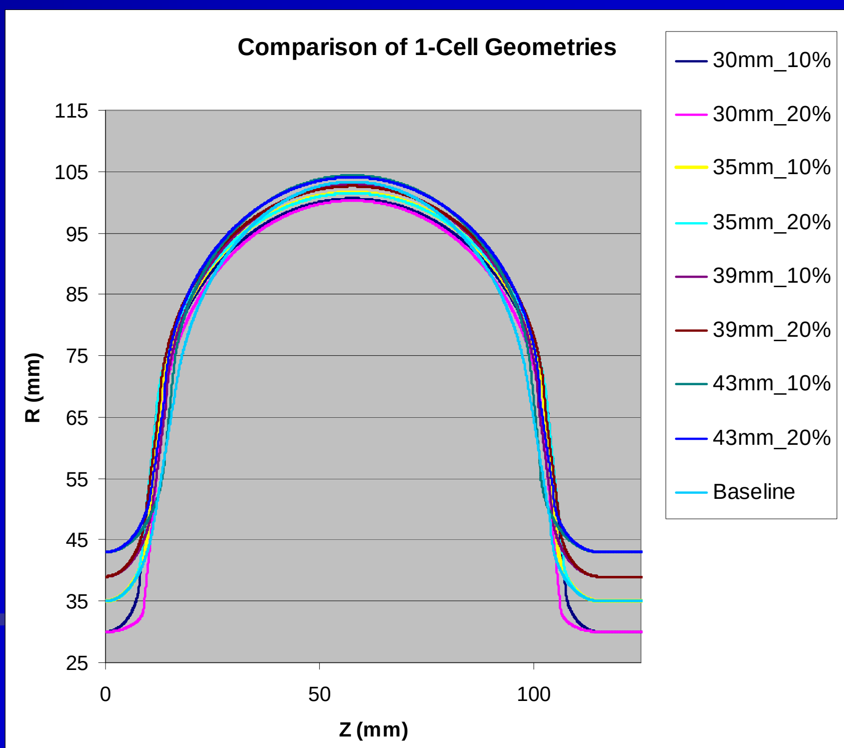
Design Approach

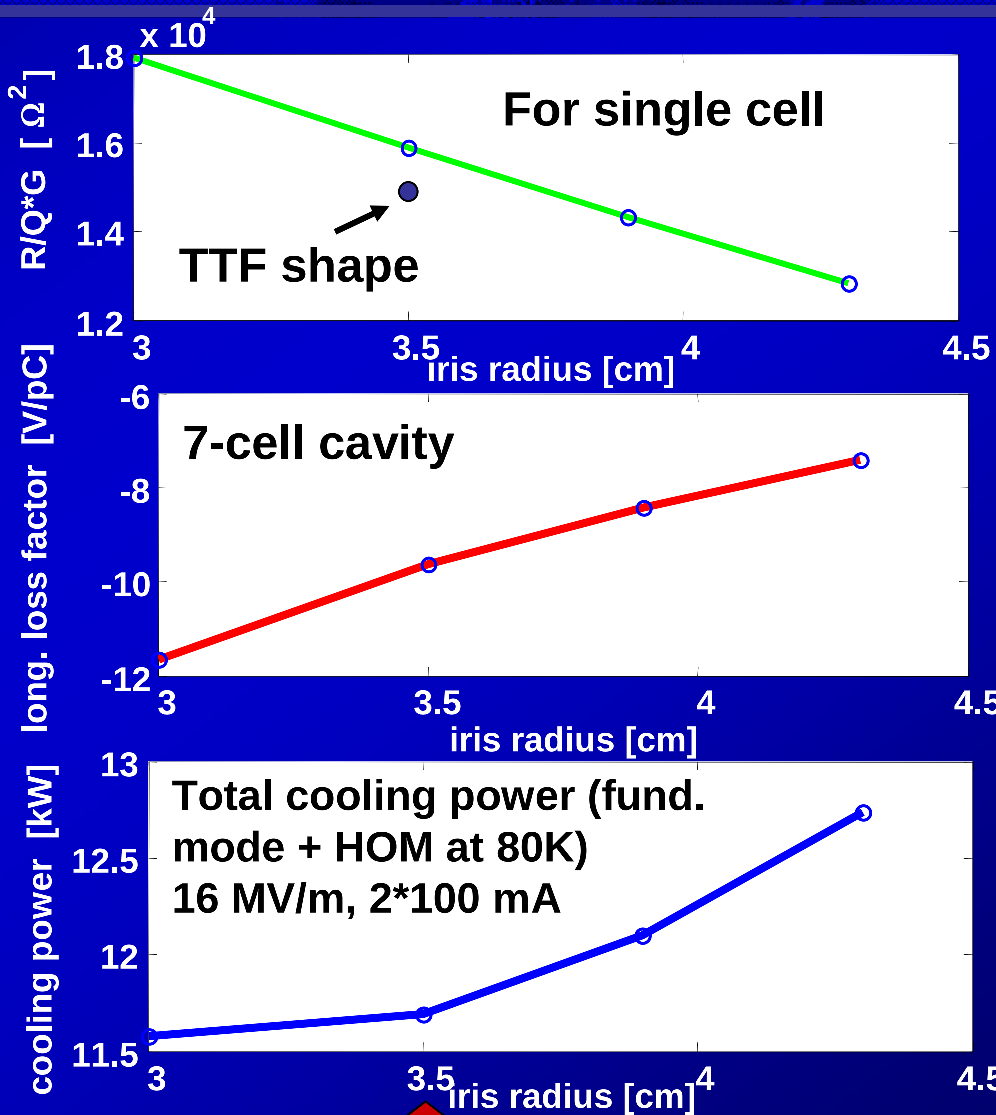
- Center cell shape optimized for low cryo-losses
- Optimize mechanical design for low microphonics
- Input coupler with opposite stub to minimize transverse kick fields
- End cells and tubes optimized for good HOM power extraction
- All higher-order monopole, and dipole modes propagate in beam tube
- Cold beamline absorbers between cavities

Cavity Cell Shape and R/Q*G

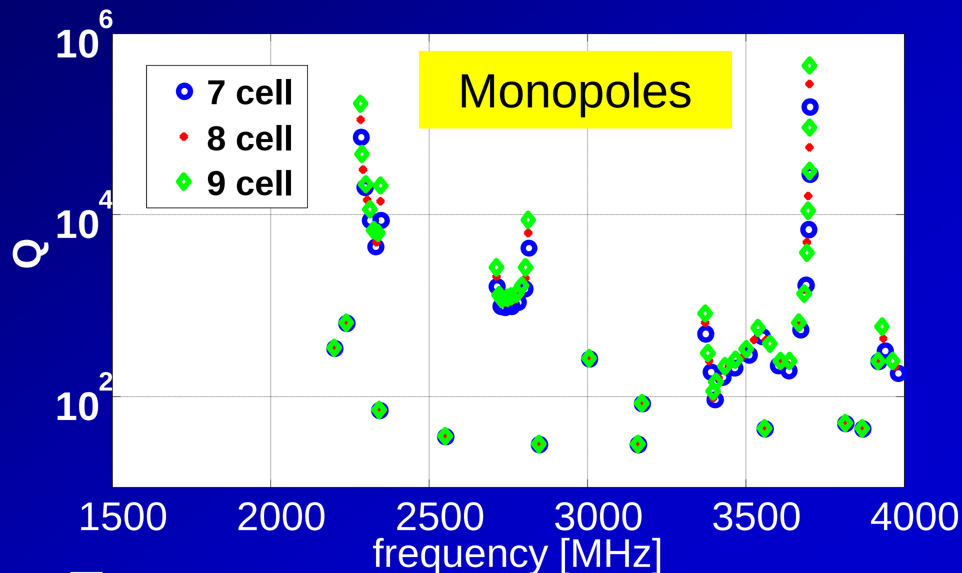
1.3 GHz center-cell:

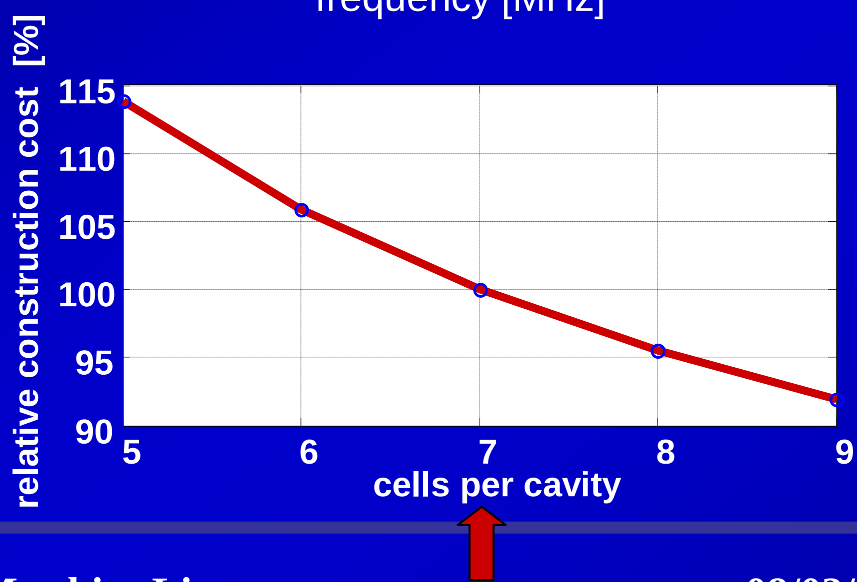
- Cells optimized for fixed side wall angle (82 deg) and electric peak field ($E/E_{acc}=2.2$)
- Selected iris radius = 35 mm





Number of Cells per Cavity





F. Marhauser at al. PAC 1999

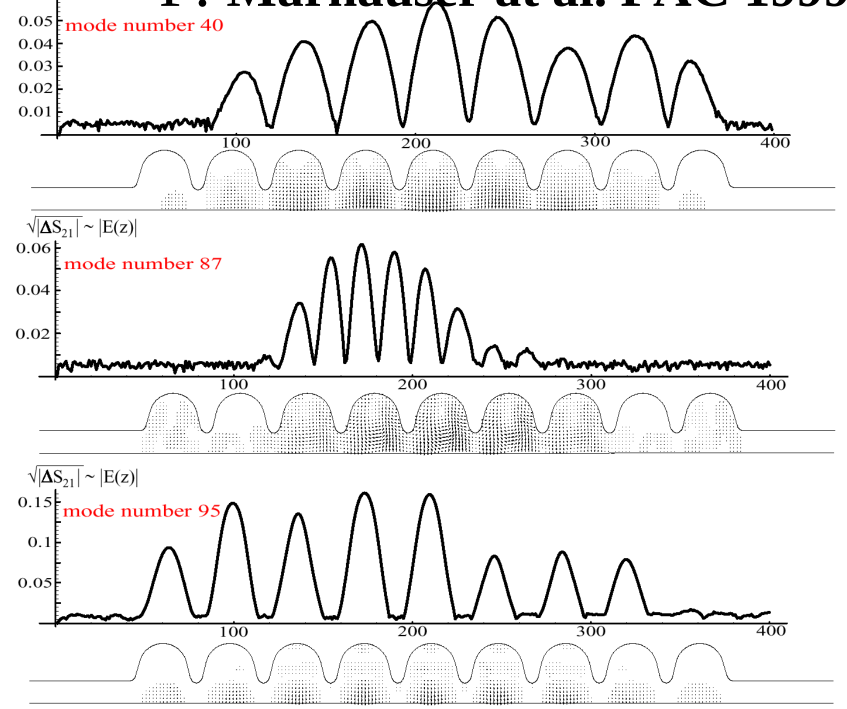
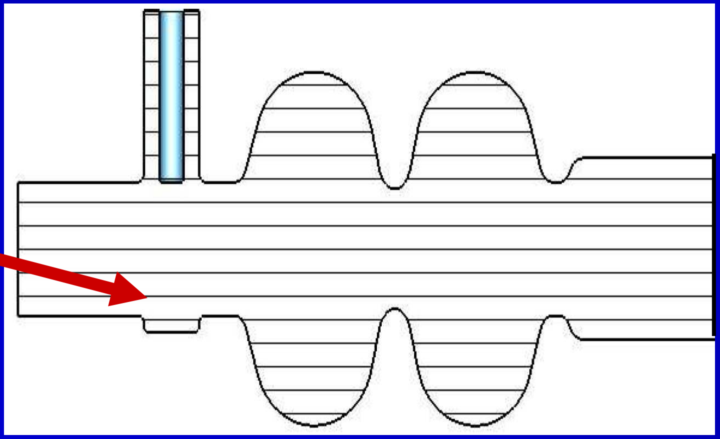


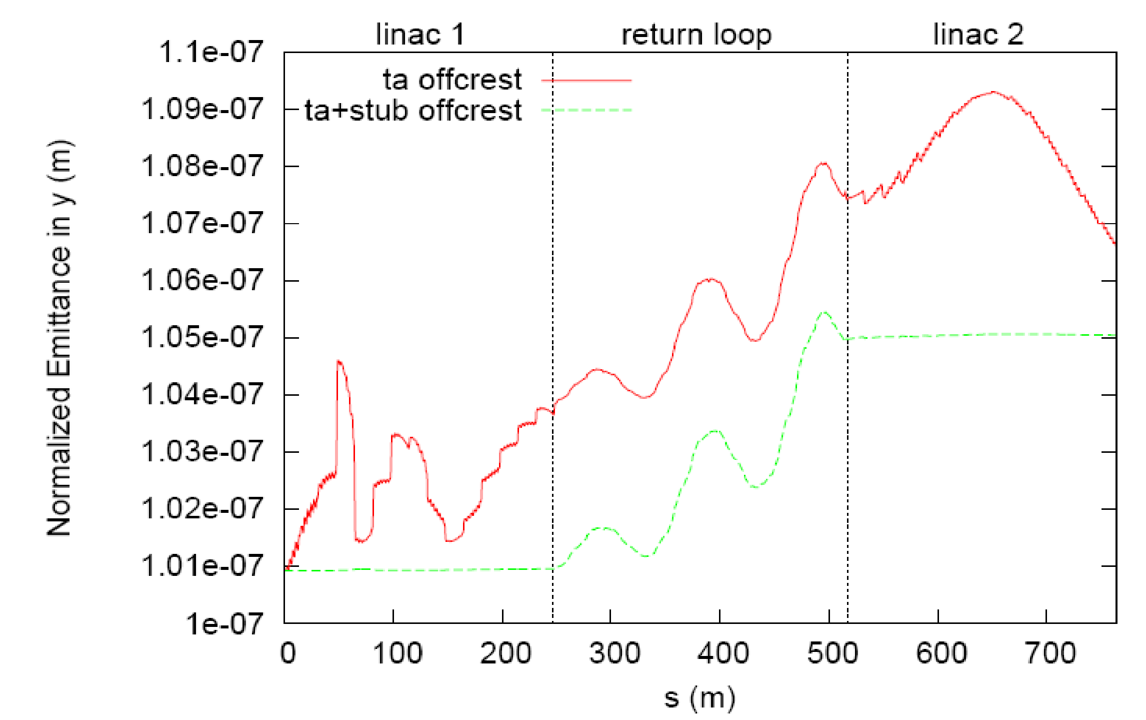
Figure 5: Trapped dipole mode (comp. Figure 4) no. 40 (f = 3.084 GHz MAFIA; 3.078 GHz meas.), mode no. 87 (f = 4.323 GHz MAFIA; 4.314 GHz meas.) and mode no. 95 (f = 4.426 GHz MAFIA; 4.421 GHz meas.).

- Risk of trapped modes increases with number of cells

Coupler Kick

Symmetrizing stub helps to reduce transverse kick fields and resulting emittance growth.



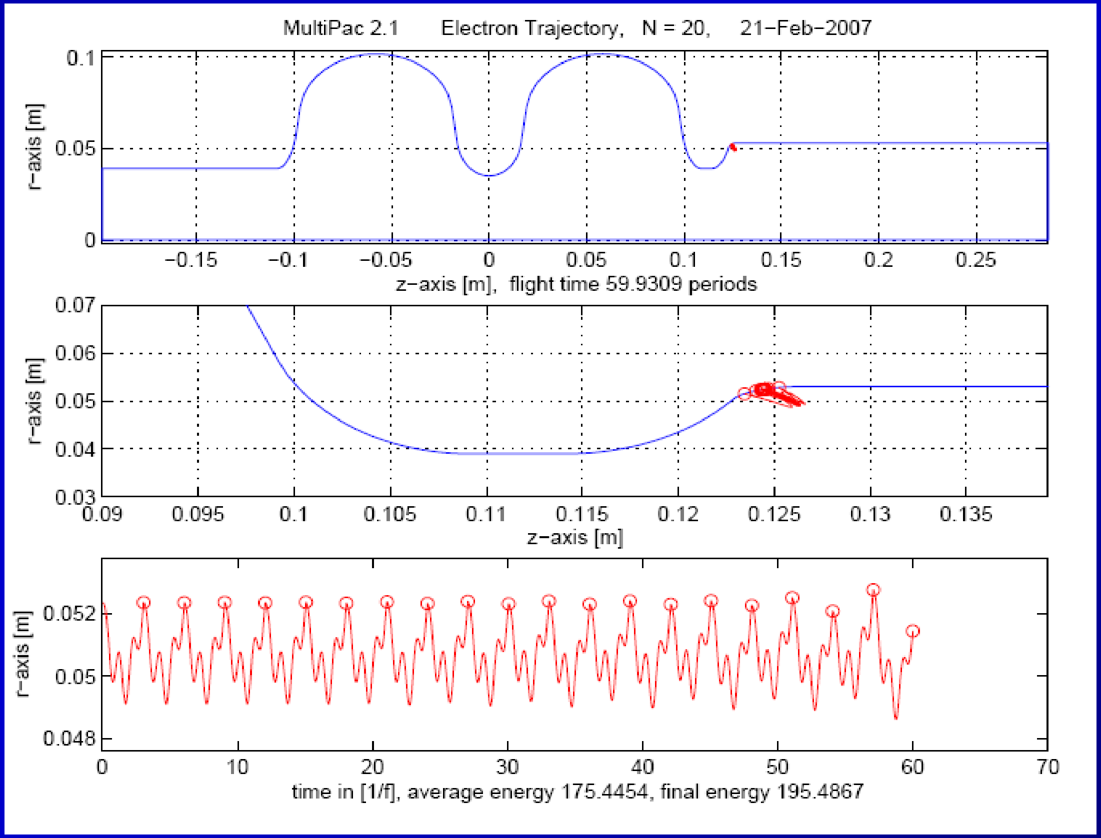


Matthias Liepe

Multipacting

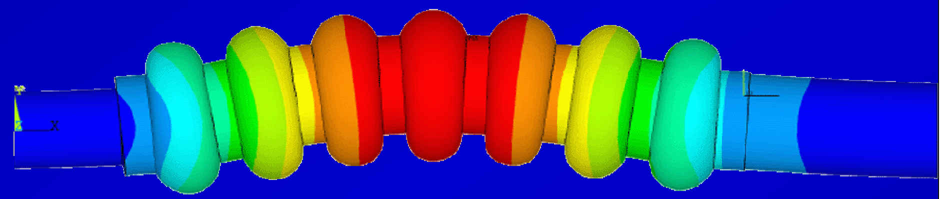
From ERL injector cavity:

- Multipacting happens 3.5-13 MV/m.
- Location is the bend of the enlarged beam tube.
- Can be processed through and can re-appear.
- If required: can modify bend region to suppress multipacting

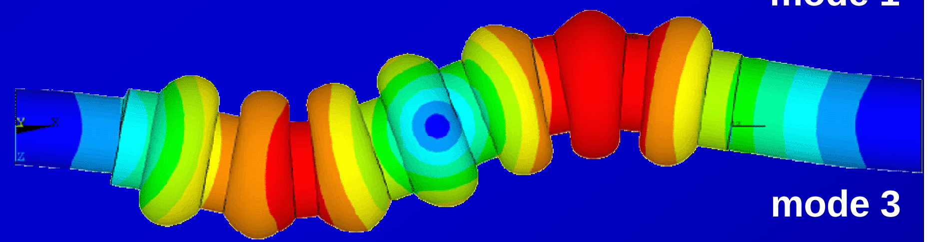


Mechanical Design for low Microphonics

- **Cavity design:**
  - High mechanical vibration frequencies
  - Low sensitivity to He-pressure changes

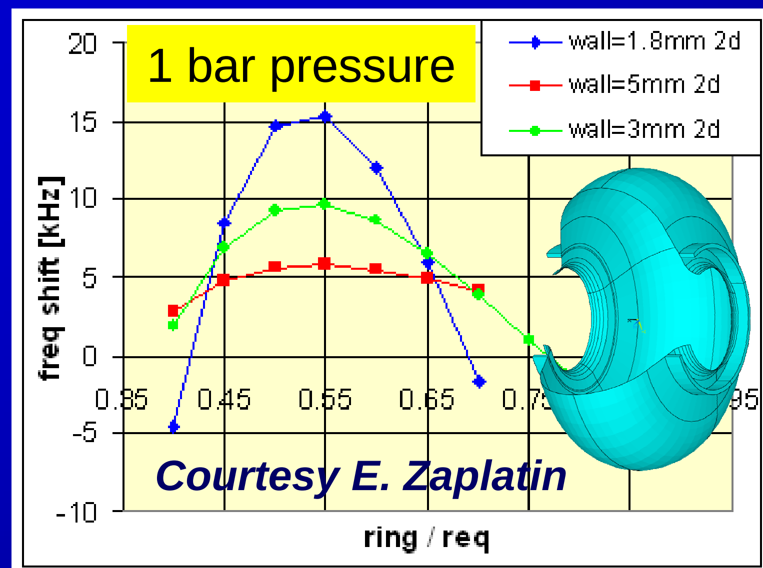


mode 1



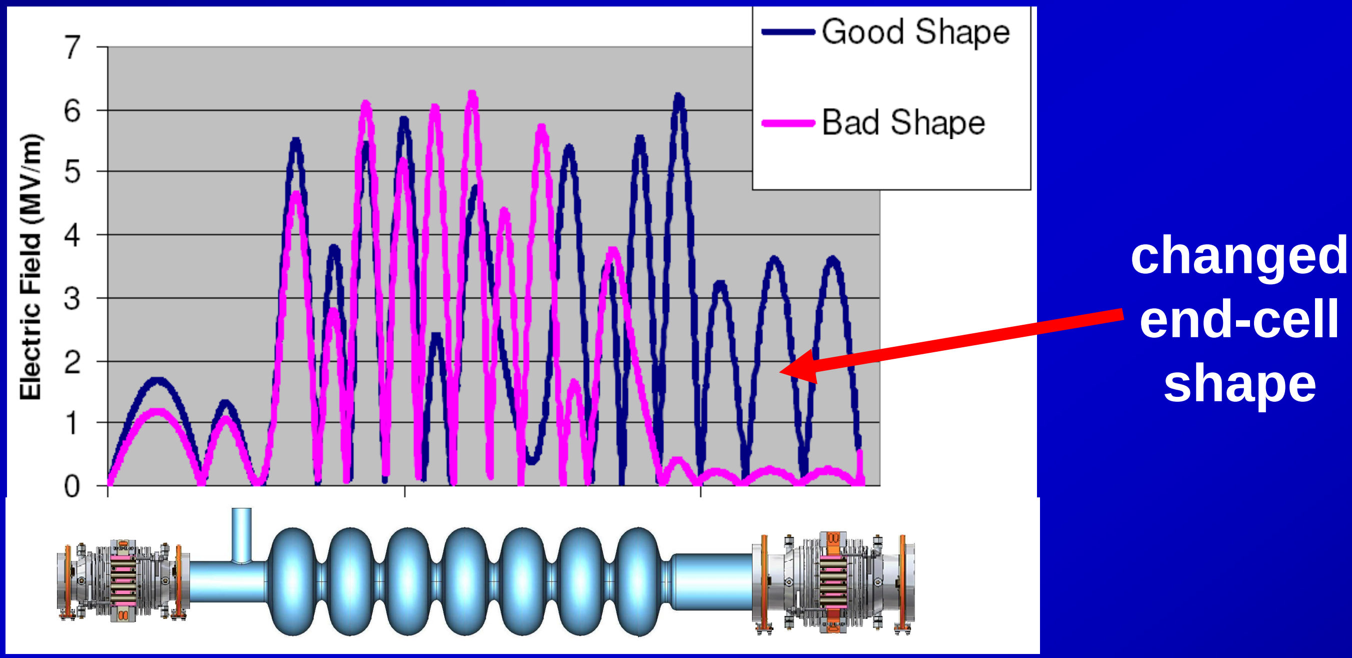
mode 3

Stif. ring	0.7*req	0.4*req	0.65*req	no ring
mode	freq / Hz	freq / Hz	freq / Hz	freq / Hz
1	131.03	85.34	115.15	54.62
2	131.04	85.33	115.15	54.62
3	315.52	191.3	268.39	133.34
4	315.52	191.3	268.39	133.34



7-Cell Cavity End-Cell Design

- End cell shape has significant impact (example HOM):



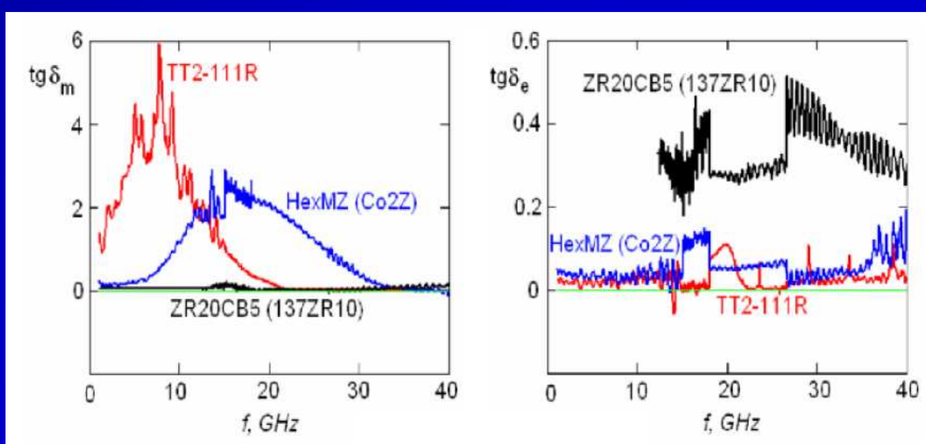
- Will use fine-tuning of end cell to
  - Increase damping of strongest dipole mode(s)
  - Avoid strong monopole modes at beam harmonics (2600 MHz, 5200 MHz, …)

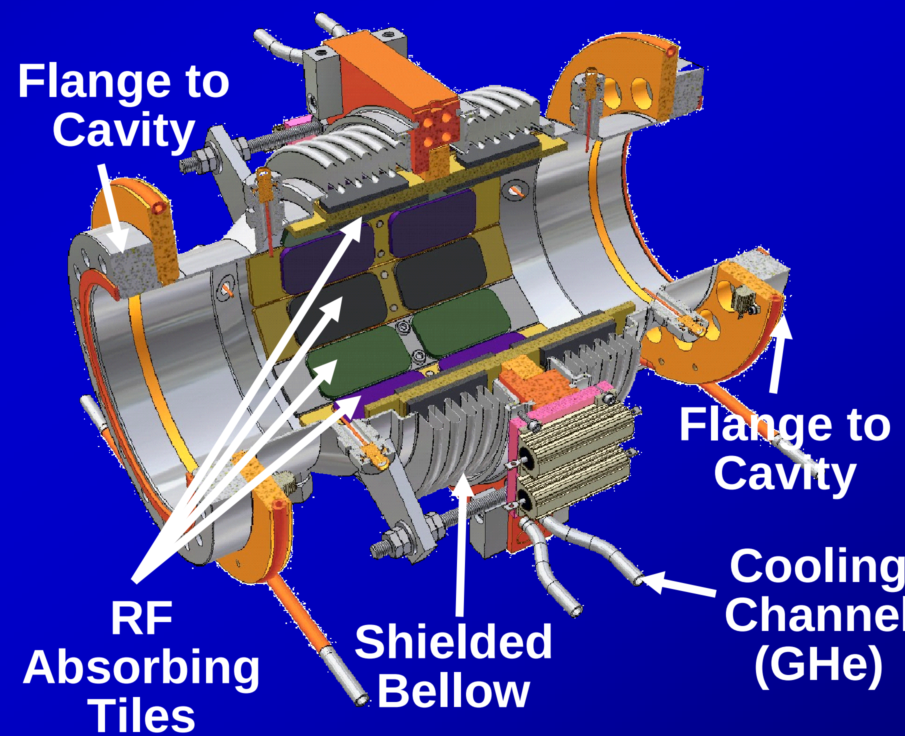
Main Linac HOM Loads

- HOM load based on injector HOM load design
- But: Higher current (factor 2) and longer cavities ⇨ significant more power to be absorbed (150 W vs. 30 W)
- Resonant HOM excitation of high frequency modes can result in even greater HOM power in a few cavities
- ⇒ Design need to support > 200 W
- Future work:
  - Design optimization (3D models)
  - Material studies
  - Improved and simplified design for higher power handling and reduced fabrication cost (reduced number of absorber tiles, only one absorbing material …)

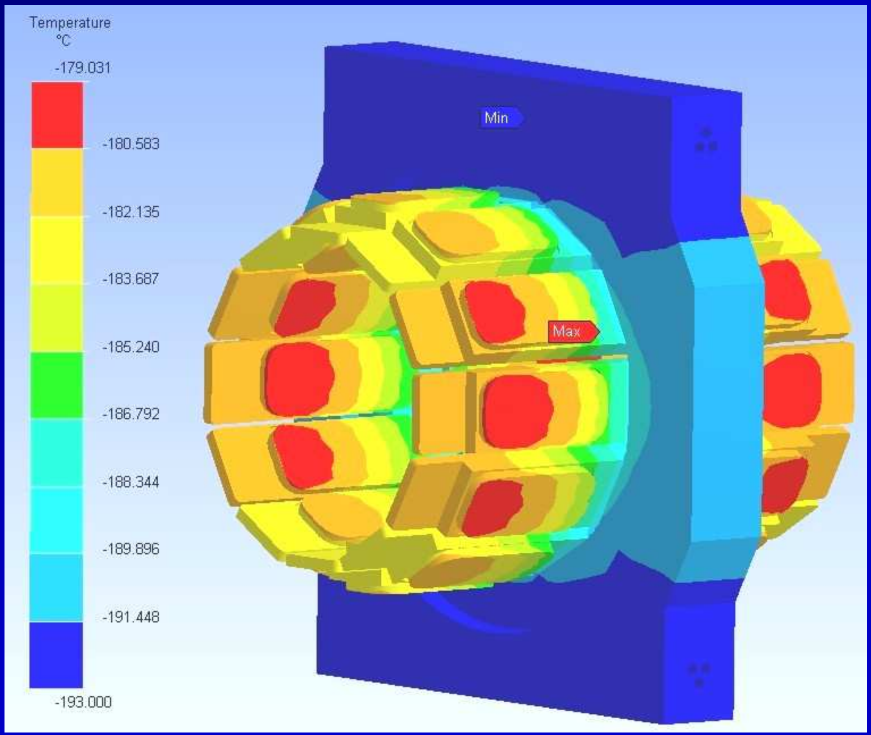
80K Cornell Beamline Absorber

- Baseline design finished
- Three RF absorbing materials selected to cover full frequency range
- <u>Full beam test in injector module in 2008</u>





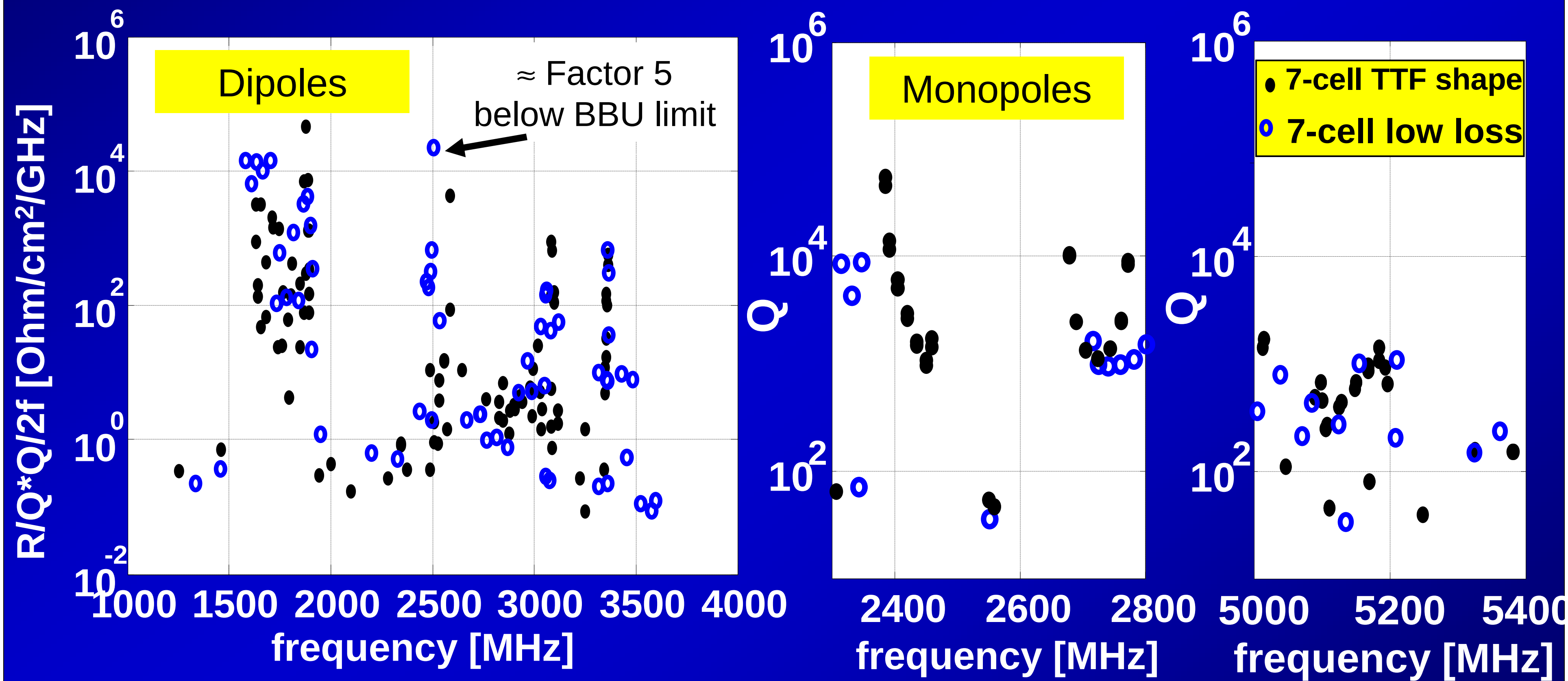
Cornell Beamline Absorber II

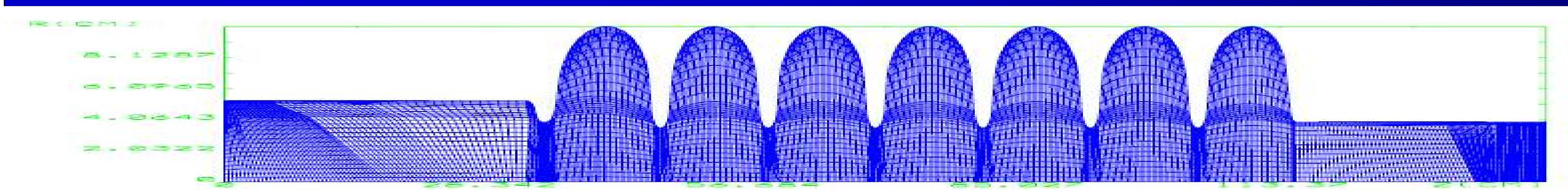


- ANSYS simulations confirm 200 W power capability
- Need to determine optimal temperature of HOM loads (probably ≈ 100 K; balance of static losses vs. better cryogenic efficiency)

HOM Damping Simulations

- CLANS calculations (started 3D Microwave Studio models)
- Modes are sufficiently damped for 100 mA operation



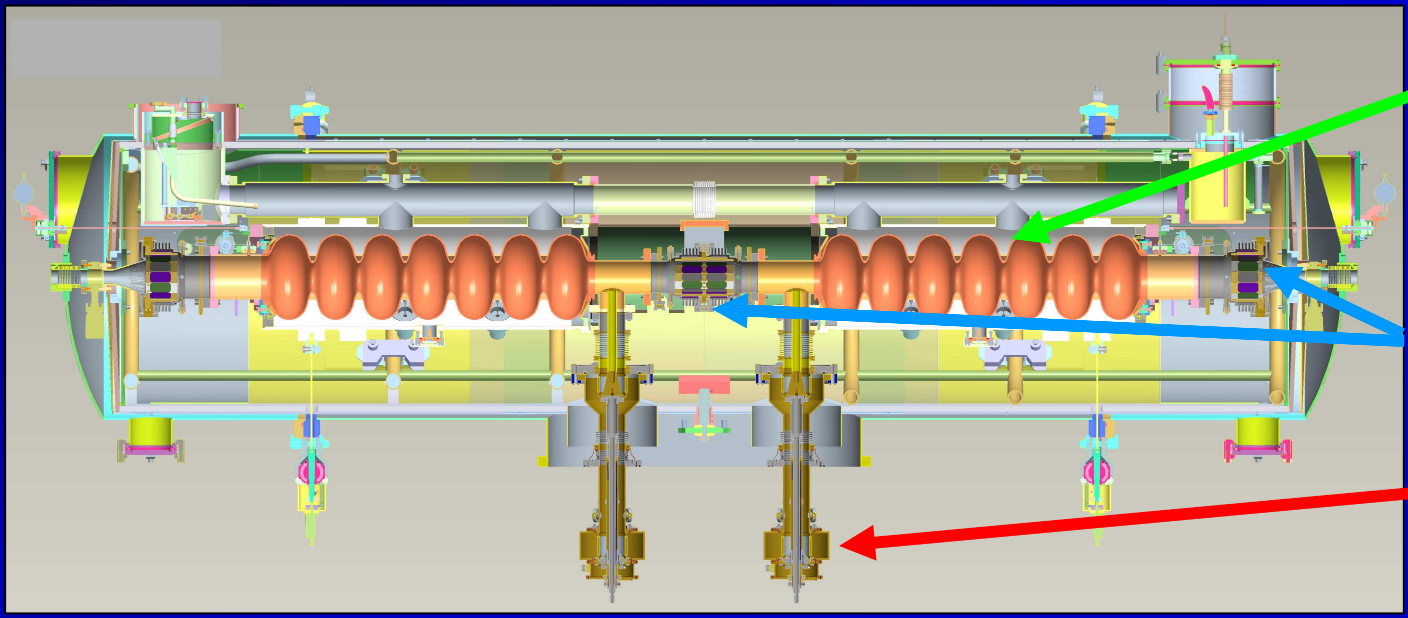


Test and R&D plans

Cavity R&D Items

- Finalize design
  - end cells
  - number of cells per cavity
  - study multipacting in more detail
- Polarized cavity to further suppress BBU?
- Study Q_0(E), microphonics level, FE, radiation and trip rates to finalize parameters
  - Results from injector cryomodule
  - Daresbury / Cornell / LBNL Test Module
  - Main linac test cryomodule
- R&D program for high Q_0 at medium fields

Daresbury / Cornell / LBNL Test Module



Two 1.3 GHz 7 cell cavities

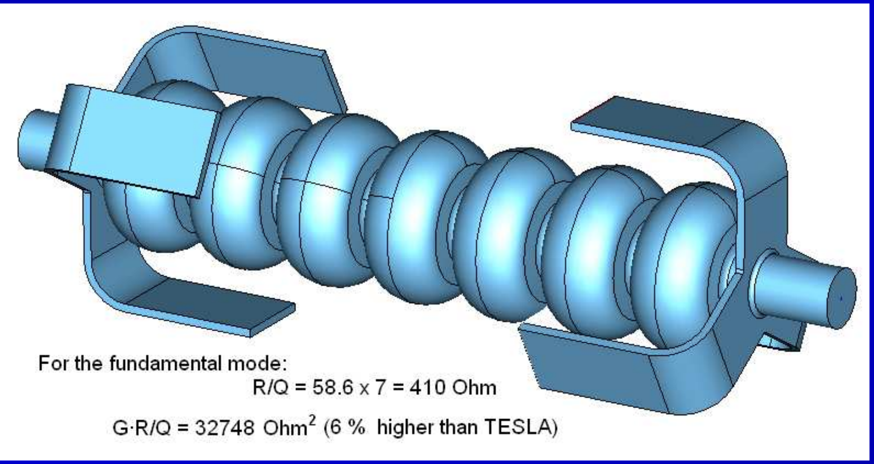
Cornell-style cold HOM load

Cornell-style input coupler (from ERL injector)

- Collaborative effort to study high-Q_0 cavity operation
  - Trip rate and Q_0 vs. gradient (long term operation planned)
  - Microphonics levels and high Q_L operation
  - Beam operation (ERLP@Daresbury)
- Modified Stanford/Rossendorf cryomodule

HOM Load R&D Items

– Optimize and simplify HOM beam line load design
– Optimize operating temperature of HOM loads
– Explore waveguide HOM damping scheme



– Verify HOM damping for main linac cavity with beam